Mine Closure 2026 – AB Fourie, G Boggs, J Heyes & M Tibbett (eds)

doi:10.36487/ACG_repo/2615_0.02

Rehabilitation in context: why evolving criteria and land use expectations matter

Lucy Commander [a,b,*], Felipe Saavedra-Mella [a], Thomas Mansfield [a], Mark Tibbett [b,c]

[a] *Forest Research Centre, Alcoa of Australia, Australia*

[b] *The University of Western Australia, Australia*

[c] *Department of Sustainable Land Management, University of Reading, UK*

Abstract

Over the past 50 years, Alcoa of Australia ('Alcoa') has invested in long-term environmental research to inform mine rehabilitation across its bauxite operations in south-west Western Australia. This paper reflects on how rehabilitation science and practice have evolved over time, driven by improved ecological understanding, operational learning, and changing societal expectations.

Expectations for rehabilitation outcomes tied to post-mining land use at Alcoa have also shifted, often involving trade-offs between objectives such as timber production and biodiversity conservation, and complexities surrounding water catchment protection and recreational access, particularly with local communities and a major metropolitan area nearby. As these priorities have evolved, so too have rehabilitation approaches, completion criteria, and monitoring frameworks.

In recent years, rehabilitation performance at Alcoa has attracted increased public scrutiny. Relevant to this scrutiny, historic rehabilitation practices can be misunderstood, stakeholders may not have a complete understanding of evolving practices, and research outputs and methods have changed over time. Public expectations of rehabilitation outcomes may not always align with agreed regulatory commitments or with what is realistically achievable in complex forest ecosystems. Rehabilitation areas must necessarily be interpreted in the context of the standards, agreed land use objectives, and scientific knowledge that applied at the time of establishment, rather than assessed just through contemporary lenses alone.

This paper emphasises the need for context aware, transparent, and reproducible approaches to describing rehabilitation outcomes, focusing on recovery progress and achievement of individual SMART (specific, measurable, achievable, relevant, time-bound) targets, rather than binary judgements about rehabilitation outcomes. It also outlines Alcoa's applied, co-designed research model, in which site-based practitioners and multidisciplinary scientific collaborators work together to address knowledge gaps, improve decision-making, and support continuous improvement in future rehabilitation outcomes.

Keywords: *completion criteria, ecosystem reconstruction, forest ecology, mine rehabilitation, restoration ecology, success criteria*

1 Introduction: long-term rehabilitation in south-west Western Australia

Mine rehabilitation is not a static discipline. Over the past 5 decades, the science underpinning rehabilitation and the practical methods used to implement it have changed substantially, informed by ecological research, operational experience, and evolving expectations of society and regulators. Rehabilitation is defined as 'the process of reinstating a level of ecosystem functionality on degraded sites where ecological restoration is not

* Corresponding author. Email address: lucy.commander@alcoa.com

the aspiration, as a means of enabling ongoing provision of ecosystem goods and services' (McDonald et al. 2016). In Australia, mine rehabilitation has moved towards an aim of achieving safe, stable, and non-polluting landforms (Lacy 2019).

More recently, expectations in the scientific literature have expanded beyond rehabilitation (management actions that aim to reinstate a level of ecosystem productivity or functioning on degraded sites) toward reinstating ecological function and, increasingly, toward aspirations for ecological restoration (the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed) and recovery (the process by which an ecosystem regains its composition, structure, and function relative to the levels identified for the reference ecosystem) (Young et al. 2022). Rehabilitation expectations are often set through environmental impact assessment processes and become conditions of approval. At the same time, there is growing recognition of delivering productivity-based post-mining land uses (PMLU) that align with, and build on, socio-economic aspirations of a region, including considerations of natural capital and respect outcomes expected by underlying tenure holders and vested stakeholders. Consequently, rehabilitation outcomes shift in context and significance over time, leaving a legacy of associated rehabilitation prescriptions (Kragt et al. 2019). This creates complex trade-offs across regulatory, community, and rightsholder aspirations that companies need to navigate in contemporary mine rehabilitation and closure processes.

Alcoa has mined bauxite in south-west Western Australia for more than 60 years, supplying alumina for global aluminium production. The region contains many land tenures with differing objectives including state forest, native title, mining leases, and reservoir protection zones. These represent, and exist alongside, a range of stakeholder groups that must continually communicate to achieve their objectives. Mining has occurred within the Northern Jarrah Forest, which is characterised by nutrient-poor soils, high plant diversity, and complex ecological processes. The region has lateritic duricrust and granitic bedrock, and long-term weathering has formed bauxite ore bodies (Soltangheisi et al. 2023). The main overstory trees consist of *Eucalyptus marginata* (jarrah) and *Corymbia calophylla* (marri), a mid-storey of Fabaceae and Proteaceae species, and a diverse understory (Gardner & Bell 2007). Bauxite mining occurs in shallow pods within a matrix of unmined forest (Koch 2007a), which results in minor changes to topography, but does not leave deep residual voids, in contrast to some of the deep open cut mines. Rehabilitation has been undertaken progressively rather than deferred until mine closure, allowing new rehabilitation prescriptions to be trialled, refined, and adopted over time. This provides a unique long-term case study of adaptive rehabilitation practice at landscape scale.

This paper uses Alcoa's decades-long rehabilitation program as a case study to explore how changing land use objectives, evolving scientific understanding, and shifts in societal expectations interact with rehabilitation criteria, monitoring, and assessment. Rather than presenting rehabilitation as a binary outcome (i.e. success versus failure), the paper encourages explicit consideration of context, trajectory, and trade-offs when describing rehabilitation performance.

2 Evolution of rehabilitation science and practice in the jarrah forest

Alcoa commenced in-house rehabilitation research in the 1970s, which has since been complemented by long-standing collaborations with consultants, government agencies, and universities. Early research focused on soil handling, re-establishment of vegetation cover, and timber productivity. Over time, research expanded to include understory diversity, fauna return, microbial community dynamics, nutrient cycling, hydrology, and longer-term ecosystem development (Koch & Hobbs 2007).

Informed by this research, rehabilitation practices have evolved over time. Initial rehabilitation involved limited landscaping, no ripping, and planting of non-local tree species (pines, cypress, eastern Australian eucalypts), primarily for timber production, according to the agreed land use of the time (Gardner & Bell 2007) and due to concerns about effects of *Phytophthora cinnamomi* (jarrah dieback) on jarrah trees (Hardy et al. 1996). Subsequent changes included reshaping pits to better reflect natural landforms, re-spreading overburden and topsoil, deep ripping to alleviate soil compaction, and introducing native understory species. From the late 1980s, rehabilitation transitioned to the exclusive use of locally native jarrah forest species, with further refinements to fertiliser application, seeding rates, seed sourcing locations (provenance), and understory species selection.

A major step change occurred with the development of propagation techniques for difficult-to-grow (recalcitrant) species in the early-1990s, enabling planting at operational scale from 1998 onwards (Grant & Koch 2007). Fertiliser application rates were continually refined as research identified long-term trade-off between rapid growth, legume dominance, and understory diversity (Daws et al. 2022, 2021, 2013). Collectively, these changes demonstrate a sustained program of adaptive management informed by long-term research over multiple decades.

3 Evolving objectives and rehabilitation expectations

The jarrah forest has been managed for a range of purposes over time, including timber production, water supply, recreation, conservation, and mineral extraction (Gardner & Bell 2007), by various Western Australian state government authorities (Grant & Koch 2007) often simultaneously and with the inherent trade-offs presented by competing requirements. Rehabilitation objectives therefore reflect agreed outcomes between the government, community, and industry.

Early agreed rehabilitation objectives emphasised productive land use, particularly timber (e.g. pine trees and non-local eucalypts), consistent with state forest management priorities of the time. Over subsequent decades, conservation values gained more prominence and expectations shifted toward reinstating a broader suite of ecosystem functions. More recently, public discourse has increasingly framed rehabilitation through the lens of ecological recovery, often expecting convergence with unmined forest conditions.

These evolving expectations raise important questions. How can rehabilitation outcomes be evaluated in relation to agreed post-mining land use objectives in forest ecosystems given known constraints and long ecological timeframes for growth and development? How should trade-offs between ecological ambition, multiple land uses, operational feasibility, and regulatory certainty be managed? How should rehabilitation outcomes be communicated to various stakeholders? These questions underline the importance of clearly articulating rehabilitation goals and aligning these goals with appropriate assessment methods for the agreed PMLU.

4 Changes in rehabilitation criteria, practice, and monitoring

Rehabilitation outcomes at Alcoa are assessed against completion criteria that are formally agreed with the Government of Western Australia Department of Industry and Resources (Department of Industry and Resources [DoIR] 2007, 2015). Completion criteria have been developed with, and approved by, Mining Management Program Liaison Group (MMPLG), which was comprised of various government department and agencies that oversee development and review of Alcoa's Mining Management Programs. MMPLG was replaced by the Bauxite Strategic Executive Committee in 2024 (Alcoa of Australia 2025). These completion criteria have been revised periodically to reflect advances in knowledge, changes in rehabilitation practice, and evolving government and community expectations. As a result, two 'eras' of rehabilitation exist across the rehabilitation estate, each with multiple updates to prescriptions and targets (Table 1). These multiple criteria result in a mosaic of operational areas under differing completion criteria within unmined forest.

Table 1 Rehabilitation eras and iterations of completion criteria (Alcoa of Australia 2025)

Rehabilitation area establishment year	Applicable completion criteria and examples of prescriptions	Reference
Early era (pre-1988)		
1966–1987	Early era (pre-1988) rehabilitation area Focused on rehabilitating to a productive land use, mainly timber production, with pines and eastern states eucalypts 1966–1972: pine trees to support timber industry 1966–1988: eastern states eucalypts for quick growth 1976–1987: native understory (mostly legumes)	DoIR (2002, 2007)
Post-1988 era		
1988–2004	Post-1988 era rehabilitation area Focused on establishing a jarrah forest ecosystem with timber production High tree stocking rates ~3,000 stems/ha (target – average 1,300 stems/ha) Fertiliser 500 kg/ha	DoIR (2002)
2005–2015	Completion criteria for 2005 onwards Target tree density maximum 2,500 and minimum 600 stems/ha at 9 months Fertiliser 280 kg/ha	DoIR (2007)
2016 onwards	Completion criteria for 2016 onwards Objective is to restore a self-sustaining jarrah forest ecosystem planned to enhance or maintain water, timber, recreation, conservation and/or nominated forest values Target tree density maximum 1,400 and average 1,000 stems/ha at 9 months Fertiliser 140 kg/ha	DoIR (2015)
Under development	Update completion criteria to recognise changes to forest management policy and current community expectations Proposed objective is to establish and return a self-sustaining jarrah forest ecosystem that meets the agreed forest values, and that will support similar management practices employed in the surrounding jarrah forest	

Rehabilitation established prior to the late 1980s reflects objectives centred on productive land use (primarily timber production), while the later era progressively incorporated biodiversity focused indicators. Rehabilitation areas established up to 1987 (referred to as early era rehabilitation areas) reflect the agreed post-mining land use at that time, which was to restore mined areas to productive land use, primarily timber production, as directed by the state (Koch 2007b). Within the post-1988 era, there have been 3 iterations of the completion criteria, with a fourth iteration currently under development. Alcoa is required, under its mining and management plan to consult with the Department for Biodiversity, Conservation and Attractions on the updated criteria. These changing practices show adaptive management and continuous improvement, as well as the benefits of research and incorporating evolving stakeholder expectations.

Applying contemporary goals or criteria to early era rehabilitation areas without accounting for this context can lead to misconstrued interpretations of rehabilitation performance. Therefore, rehabilitation performance must be assessed relative to the agreed post-mining land use, objectives, methods, and knowledge applied at the time of establishment.

5 Interpreting historic rehabilitation against agreed objectives

Interpreting historic rehabilitation outcomes requires consideration of the objectives and completion criteria in place at the time of establishment. Rehabilitation practices and expectations have evolved alongside scientific and social progression. Subsequently, assessments undertaken outside of agreed regulatory criteria may apply benchmarks that differ from those used at the time of establishment. This creates a need to distinguish between original design intent and current expectations when evaluating historic rehabilitation.

Portions of historic rehabilitation have been assessed as meeting the agreed post-mining land use objectives and completion criteria that applied at the time, and have been granted certificate of acceptance and returned to the Government of Western Australia (Grant & Koch 2007). These areas were designed and rehabilitated to support productive forest outcomes, primarily timber production. Post-1988 era rehabilitation reflects a shift in objectives toward establishing a self-sustaining jarrah forest ecosystem, with corresponding changes in objectives, completion criteria and performance expectations.

Apparent differences in performance can arise where rehabilitation outcomes are interpreted using criteria that were not part of its original design. In some cases, criteria developed for Post-1988 era rehabilitation, or derived from non-regulatory ecological frameworks, when applied to areas established under different design assumptions, can create a mismatch between intended outcomes and assessed performance. Consistent interpretation therefore requires alignment between post-mining land use, completion criteria, and objectives in place at the time of establishment, particularly where assessment approaches and expectations vary across scientific and public contexts.

6 Public scrutiny, perception, and communication challenges

Rehabilitation performance has attracted increasing public scrutiny, informed by heightened expectations for environmental outcomes and by the growing use of high-level frameworks, such as the *International Principles and Standards for the Ecological Restoration and Recovery of Mine Sites (Mine Site Restoration Standards, MSRS)* (Young et al. 2022). While such frameworks can provide valuable conceptual guidance, misalignment between aspirational benchmarks from the public or academia, and regulatory criteria agreed to with governments, can generate misunderstanding, particularly when some may perceive rehabilitation results as full replication of pre-disturbance species composition.

In many rehabilitation contexts, the primary objective is the recovery of ecosystem function rather than the return of the full suite of original species. This includes the re-establishment of processes such as soil stabilisation, nutrient cycling, hydrological regulation, primary productivity, and the capacity of vegetation to persist and regenerate without ongoing intervention. Functional recovery can support biodiversity over time and may precede, or occur independently of, the return of the full suite of species associated with mature reference ecosystem. Also, it represents a shift in the system from a degraded state, and initiates a trajectory of ecological recovery.

The use of binary language, particularly terms ‘success’ and ‘failure’ can polarise debate and obscure complexities that exist in the continuum of rehabilitation activities and long-term ecosystem development. Rehabilitation outcomes are more meaningfully described in terms of the extent to which ecosystem functions are reinstating, whether ecological trajectories are consistent with agreed land use objectives, how trade-offs have been managed within regulatory and operational constraints, and whether completion criteria are met. Transparent communication of what rehabilitation is designed to achieve and how functional and structural attributes are improving over time is essential to address community trust and social licence

(Rosa et al. 2020). Relevant and audience-specific communication of scientific and rehabilitation outcomes remains a key aspect of mine rehabilitation that should be continually improved.

7 Assessing rehabilitation

7.1 Beyond binary judgements: rethinking 'success' and 'failure'

Assessing the 'success' of rehabilitation and communicating outcomes can be challenging. Koch & Hobbs (2007) discussed whether Alcoa is successfully restoring a jarrah forest ecosystem. They discussed various ways of measuring success and noted that a single measure does not exist. In the same year, Zedler (2007) criticised the terms "success" and "failure". She noted that more specific terms would achieve clarity, such as "restoration status", "success criteria", and "transplant survival", and clarified when making a value judgement, such as "in my opinion, it was a success" (Zedler 2007). This point aligns with Koch & Hobbs (2007) who were using specific indicators to measure success rather than judging rehabilitation outcomes as a singular project. Since these papers were published in 2007, new guidance around completion criteria has been released (Young et al. 2019). Alcoa's completion criteria were used as practical examples of leading and proxy indicators.

Defining rehabilitation success is further complicated by relatively short observed timescales, with only hypothetical models to estimate how a jarrah forest ecosystem under rehabilitation may fully develop (*sensu* Grant 2006). For instance, attempts are made to forecast the success of post-1988 rehabilitation (1 to 38-year-old) against a reference ecosystem which has been subjected to timber harvesting (possibly more than once) and may also be on a recovery trajectory, despite the likelihood that immature rehabilitation will continue to develop non-linearly over time. Taken together, the term 'rehabilitation success' is clearly multifaceted, not binary, and may better be represented by a rehabilitation 'health' evaluation which draws together tailored measures of ecosystem functionality and reference similarity, and identifies areas where adaptive management may be required.

7.2 Interpreting outcomes through time: historic rehabilitation and era-specific context

Ultimately, rehabilitation needs to be assessed against the era-specific completion criteria that are agreed with the regulator. Knowledge of specific prescriptions and key milestones within rehabilitation eras is important for guiding the assessment of historic rehabilitation. For instance, knowing that recalcitrant species were planted from 1992 but were not in operational levels until 1998, is important context when assessing understory species richness and density during that time. This temporal perspective underscores the importance of aligning evaluation not only with ecological benchmarks but also with the practical and regulatory constraints under which rehabilitation was undertaken. Without that context, erroneous judgements could be made.

7.3 From principles to practice: contemporary frameworks and measurement challenges

Various frameworks have been developed to inform rehabilitation goal and target setting, what to measure to assess if the targets are met, how to measure, and how to communicate the outcomes. Rehabilitation can be assessed using a variety of techniques and methodologies and these techniques and methodologies have advanced since Alcoa commenced rehabilitation in the 1960s.

A diverse suite of ecological restoration frameworks have been developed from various perspectives and written for a range of audiences and purposes. New regional and global frameworks that have been developed include the *International Principles and Standards for the Ecological Restoration and Recovery of Mine Sites (Mine Site Restoration Standards, MSRS)* (Young et al. 2022), *International Principles and Standards for the Practice of Ecological Restoration* (Gann et al. 2019), the *National Standards for the Practice of Ecological Restoration in Australia* (McDonald et al. 2016) and *The SER International Primer on Ecological Restoration* (SERI Science & Policy Working Group 2004). Another framework with the potential to assess rehabilitation and communicate its outcomes is the *System of Environmental-Economic Accounting (SEEA)*

Central Framework (Parkhurst et al. 2025). Mine closure guidance documents at a global and regional level have also been developed (e.g. see main guidance documents within Guj & Rogerson (2024) and *A Framework for Developing Mine-Site Completion Criteria in Western Australia* (Young et al. 2019), but may be written for different target audiences (government or industry). Mine closure documents vary in their level of detail (Guj & Rogerson 2024) but are ultimately developed with a specific focus on the mining industry and its specific context, as opposed to being nested within an environmental conservation context.

Despite this array of frameworks and documents, some guidance on goals, targets and monitoring is very high level. For some attributes, guidance on developing good SMART targets (specific, measurable, achievable, relevant, time-bound; see Manero et al. 2020 for a rehabilitation-specific description) and what methods can be used to measure them may not be available. The Mining Ecological Recovery Wheel (Young et al. 2022), for instance, lists gene flows, landscape flows, and habitat interactions as attributes to be measured, and provides guidance on how to score them on a scale of one to five. Once attributes and SMART targets are set, appropriate monitoring methodologies and monitoring frequency need to be determined. It would be useful to have monitoring methodologies for these attributes if they are indeed considered critical for mine closure, as some attributes, such as gene flow, are almost impossible to quantify for every species; however, more recent guidance has suggested using pollinator observations or genomic data as examples of evidence (Bartholomew et al. 2024; Bishop & Young 2025). In fact, *The SER International Primer on Ecological Restoration* states that some attributes are readily measured, whereas others must be assessed indirectly and may not be determined without research efforts beyond the scope and budget of most restoration projects (SERI Science & Policy Working Group 2004). Nutrient cycling, for instance, is mostly inferred rather than a direct measurement, resilience is rarely studied (except for Mediterranean forests in south-west Western Australia), and indicators of ‘self-sustainability’ are not often reported (Harries et al. 2024). Adaptive management guidelines to undertake remediation if targets aren’t met would also be useful for key attributes.

Monitoring techniques to measure SMART targets have advanced over time. Traditional vegetation surveys remain fundamental, but are increasingly complemented by new technologies such as remote sensing, camera traps, ecoacoustics, and eDNA which can now be used to assess rehabilitation (Liddicoat et al. 2022; Stephenson 2020), plus improved data integration, AI and machine learning. While these advancements enhance understanding of rehabilitation trajectories, they do not retrospectively alter historical objectives or obligations, and interpretation of their outputs should be framed by individual rehabilitation prescriptions.

In terms of communicating outcomes and data from monitoring, given that the mining ecological recovery wheel is a generic framework, mining companies could use their own completion criteria to populate the wheel, rather than the template attributes suggested in the framework, as the wheel is a tool that can be adapted to suit the context. Consequently, tailoring generic recovery frameworks with site-specific attributes agreed on with the regulatory authorities will foster the development of more appropriate and science-backed rehabilitation objectives, targets, and monitoring methods. Perhaps a more pertinent question is, how do we better communicate rehabilitation outcomes? The recovery wheel and SEEA are options, but other formats such as dashboards, could be used, as long as they are used to communicate the agreed targets.

8 Practical considerations for ecological goals

Given the challenging nature of mine rehabilitation, how do we balance the aspirational and the practical? The *Mine Site Restoration Standards* (Young et al. 2022) states ‘When native ecosystems are impacted by mining, full recovery informed by reference models should be the target.’ However, it also states ‘Where this is not achievable a “recovery gap” between the initial native ecosystem and the post-mining ecosystem is created.’ This statement implies that the aspirational may not be practically achievable. One option to address this issue is to set ‘primary’ and ‘minimum’ restoration goals, to optimise outcomes so broader restoration outcomes can be achieved in the long-term (primary goal), while enabling completion and evaluation within a reasonable timeframe (minimum goal) (Government of Western Australia 2018).

Can mine closure and ecological aspirations meet in the middle? Mine rehabilitation/closure and ecological restoration are two disciplines that have emerged separately, with rehabilitation focused on creating a safe, stable and non-polluting landscape, while restoration sought to reinstate a functioning ecosystem. Over time, these 2 disciplines have merged with increasing expectations from some stakeholders that mine rehabilitation should produce ecosystems identical to the pre-mining area. However, given the timescales required to fully understand the recovery trajectory, plus the extent to which the soil profile may have been reconstructed, this may not always be a realistic expectation. There may be a middle ground, by which mine rehabilitation recognise that a highly diverse, ecologically functional and integrated community is aspirational and achievable, but this is not the same as the pre-mining area. Hence, the aspiration is achievable in principle, by using locally indigenous reference ecosystems and progressing as far as possible along the recovery trajectory while acknowledging constraints such as altered site conditions, propagation challenges, and the scale of intervention required. In fact, the intent of the *Mine Site Restoration Standards* is to inspire better outcomes by guiding and encouraging the highest achievable level of rehabilitation (Young et al. 2022). In this case, how can stakeholder expectations be managed effectively, mining companies communicate transparently, and misinterpretation and misunderstandings be managed? Having clear and transparent goals and targets that are well communicated could help avoid misunderstandings. Nevertheless, the challenge remains of how to report rehabilitation outcomes against these targets in a clear and effective way.

9 Applied, co-designed research for continuous improvement

Principle 5 of the National Standards for the Practice of Ecological Restoration in Australia recognises that restoration science and practice are synergistic, and acknowledges that ecological restoration is a rapidly emerging practice that often relies upon processes of trial and error (McDonald et al. 2016). Alcoa has long recognised the importance of having an in-house research team (Grant & Koch 2007), collaborations with universities, government, and consultants, as well as the support of champions within the business including environmental managers and leadership (Gardner & Bell 2007). This leadership aimed to keep Alcoa ahead of legislative requirements. In 2007, Gardner & Bell noted that 'Predicting the community's future expectations for environmental and restoration performance is difficult', and a research team enabled expectations to be collaboratively anticipated and explored. Since 1975, Alcoa has supported the publication of more than 250 refereed journal papers and book chapters, 80 technical studies, and about 60 higher degree research theses. Maintaining research outputs is critical for both continuous operational improvement and enhanced environmental outcomes, as well as providing data-based and transparent external communication, and licence to operate.

Alcoa is continuing research through the Forest Research Centre, a 5-year commitment with an uplift in staff and funding. The research centre encompasses rehabilitation, flora, fauna, water, and cross-cultural science. Research is undertaken by the internal team of experts, as well as through collaborative projects with scientists in Western Australia, Australia and internationally. By co-designing research with end users within the company, the research outputs can directly feed back into on-ground management and incorporated into practices. Outputs can also benefit those working in the region, as well as the global scientific community.

10 Conclusion

Mine rehabilitation in complex ecosystems cannot be meaningfully described through static or binary assessments, nor from the perspective of a specific discipline or sub-sector viewpoint. The activity is industry-specific and needs to be considered from that vantage. Alcoa's experience in the jarrah forest illustrates the importance of context, including evolving land use objectives, changing rehabilitation practices, and long ecological timeframes. Accordingly, assessment frameworks should be explicitly aligned with the post-mining land use, goals, objectives, knowledge, and standards that were applied at the time of establishment, while recognising rehabilitation as a trajectory rather than a fixed end point. Emphasising functional recovery, transparency in trade-offs, and clear communication of progress can help bridge gaps between regulatory commitments, scientific reality, and public expectations. In addition, we provide some suggestions for contemporary frameworks that guide and assess current rehabilitation efforts. The lessons outlined in this case study are broadly applicable to global mine closure planning where the challenge is not only to rehabilitate landforms but to navigate the intersection of science, regulation, and societal expectation in a credible, adaptive and transparent manner.

Acknowledgements

Thanks to Guy Boggs, Justin Jonson, Renee Young, and six additional reviewers for providing advice.

Use of artificial intelligence disclosure statement

In the preparation of this work, the authors used Microsoft Copilot (version M365) to improve the language and clarity of the text. The authors have reviewed the content and edited it where required and take full responsibility for said content.

References

Alcoa of Australia 2025, *Pinjarra Alumina Refinery Revised Proposal Environmental Review Document*, Perth.

Bartholomew, DC, Mosyaftiani, A, Morgan, B, Shah, T, Shaw, K, Stillman, C, Baldwin, K, Baqueiro, L, Birkinshaw, C & Breman Jr, E 2024, *The Global Biodiversity Standard: Manual for Assessment and Best Practices*, Botanic Gardens Conservation International & Society for Ecological Restoration, Richmond.

Bishop, H & Young, R 2025, *Restoration standards for the Western Australian Wheatbelt*, The Western Australian Biodiversity Science Institute.

Daws, MI, Blackburn, C, Standish, RJ & Tibbett, M 2022, 'Canary in the coal mine: Lessons from the Jarrah Forest suggest long-term negative effects of phosphorus fertilizer on biodiverse restoration after surface mining', *Frontiers in Forests and Global Change*, vol. 5, pp. 786305.

Daws, MI, Standish, RJ, Koch, JM & Morald, TK 2013, 'Nitrogen and phosphorus fertilizer regime affect jarrah forest restoration after bauxite mining in Western Australia', *Applied Vegetation Science*, vol. 16, no. 4, pp. 610–618.

Daws, MI, Walters, SJ, Harris, RJ, Tibbett, M, Grigg, AH, Morald, TK, Hobbs, RJ & Standish, RJ 2021, 'Nutrient enrichment diminishes plant diversity and density, and alters long-term ecological trajectories, in a biodiverse forest restoration', *Ecological Engineering*, vol. 165, pp. 106222.

Department of Industry and Resources (DoIR) 2002, *Alcoa World Alumina Australia Darling Range Bauxite Mine Rehabilitation Completion Criteria*, Government of Western Australia, Perth.

Department of Industry and Resources (DoIR) 2007, *Alcoa World Alumina Australia Darling Range Bauxite Mine Rehabilitation Completion Criteria*, Government of Western Australia, Perth.

Department of Industry and Resources (DoIR) 2015, *Alcoa's Bauxite Mine Rehabilitation Program. Completion Criteria and Overview of Area Certification Process. 2015 Revision*, Government of Western Australia, Perth.

Gann, GD, McDonald, T, Walder, B, Aronson, J, Nelson, CR, Jonson, J, Hallett, JG, Eisenberg, C, Guariguata, MR, Liu, J, Hua, F, Echeverría, C, Gonzales, E, Shaw, N, Decleer, K & Dixon, KW 2019, 'International principles and standards for the practice of ecological restoration. Second edition', *Restoration Ecology*, vol. 27, no. S1, pp. S1–S47.

Gardner, JH & Bell, DT 2007, 'Bauxite mining restoration by Alcoa World Alumina Australia in Western Australia: social, political, historical, and environmental contexts', *Restoration Ecology*, vol. 15, no. suppl. 4, pp. S3–S10.

Government of Western Australia 2018, *Rehabilitating Roe 8 Rehabilitation Management Plan*, Perth.

Grant, CD 2006, 'State-and-transition successional model for bauxite mining rehabilitation in the jarrah forest of Western Australia', *Restoration Ecology*, vol. 14, no. 1, pp. 28–37.

Grant, C & Koch, J 2007, 'Decommissioning Western Australia's First Bauxite Mine: Co-evolving vegetation restoration techniques and targets', *Ecological Management & Restoration*, vol. 8, no. 2, pp. 92–105.

Guj, P & Rogerson, R 2024, *Mine Closure Guidance: Review and Comparative Analysis*, CRC TiME, Perth.

Hardy, GESJ, Colquhoun, IJ & Nielsen, P 1996, 'The early development of disease caused by *Phytophthora cinnamomi* in *Eucalyptus marginata* and *Eucalyptus calophylla* grooving in rehabilitated bauxite mined areas', *Plant Pathology*, vol. 45, no. 5, pp. 944–954.

Harries, KL, Woinarski, J, Rumpff, L, Gardener, M & Erskine, PD 2024, 'Characteristics and gaps in the assessment of progress in mine restoration: insights from five decades of published literature relating to native ecosystem restoration after mining', *Restoration Ecology*, vol. 32, pp. e14016.

Koch, JM 2007a, 'Alcoa's Mining and Restoration Process in South Western Australia', *Restoration Ecology*, vol. 15, no. s4, pp. S11–S16.

Koch, JM 2007b, 'Restoring a jarrah forest understorey vegetation after bauxite mining in Western Australia', *Restoration Ecology*, vol. 15, no. 4, pp. S26–S39.

Koch, JM & Hobbs, RJ 2007, 'Synthesis: is Alcoa successfully restoring a jarrah forest ecosystem after bauxite mining in Western Australia?', *Restoration Ecology*, vol. 15, no. 4, pp. S137–S144.

Kragt, ME, Manero, A, Hawkins, J & Lison, C 2019, *A Review of Mine Rehabilitation Condition Setting in Western Australia*, The Western Australian Biodiversity Science Institute, Perth.

Lacy, HWB 2019, 'Mine landforms in Western Australia from dump to landform design: review, reflect and a future direction', in AB Fourie & M Tibbett (eds), *Mine Closure 2019: Proceedings of the 13th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 371–384, https://doi.org/10.36487/ACG_rep/1915_30_Lacy

Liddicoat, C, Krauss, SL, Bissett, A, Borrett, RJ, Ducki, LC, Peddle, SD, Bullock, P, Dobrowolski, MP, Grigg, A, Tibbett, M & Breed, MF 2022, 'Next generation restoration metrics: Using soil eDNA bacterial community data to measure trajectories towards rehabilitation targets', *Journal of Environmental Management*, vol. 310, pp. 114748.

Manero, A, Kragt, M, Standish, R, Miller, B, Jasper, D, Boggs, G & Young, R 2020, 'A framework for developing completion criteria for mine closure and rehabilitation', *Journal of Environmental Management*, vol. 273, pp. 111078.

McDonald, T, Jonson, J & Dixon, K 2016, 'National Standards for the Practice of Ecological Restoration in Australia', *Restoration Ecology*, vol. 24(S1), pp. 1–34.

Parkhurst, T, Commander, L & Standish, RJ 2025, 'Global ecosystem accounting standard: a solution to monitor, mitigate, and transparently report global mining impacts in support of biodiversity goals', *One Earth*, vol. 8, no. 9, pp. 101430.

Rosa, JCS, Morrison-Saunders, A, Hughes, M & Sánchez, LE 2020, 'Planning mine restoration through ecosystem services to enhance community engagement and deliver social benefits', *Restoration Ecology*, vol. 28, no. 4, pp. 937–946.

SERI Science & Policy Working Group 2004, *The SER International Primer on Ecological Restoration*, Tucson.

Soltangheisi, A, George, S & Tibbett, M 2023, 'Soil Characteristics and Fertility of the Unique Jarrah Forest of Southwestern Australia, with Particular Consideration of Plant Nutrition and Land Rehabilitation', *Land*, vol. 12, no. 6, pp. 1236.

Stephenson, PJ 2020, 'Technological advances in biodiversity monitoring: applicability, opportunities and challenges', *Current Opinion in Environmental Sustainability*, vol. 45, pp. 36–41.

Young, R, Manero, A, Miller, B, Kragt, M, Standish, RJ, Jasper, D & Boggs, G 2019, *A Framework for Developing Mine-Site Completion Criteria in Western Australia*, The Western Australian Biodiversity Science Institute, Perth.

Young, RE, Gann, GD, Walder, B, Liu, J, Cui, W, Newton, V, Nelson, CR, Tashe, N, Jasper, D, Silveira, FAO, Carrick, PJ, Hägglund, T, Carlsén, S & Dixon, K 2022, 'International principles and standards for the ecological restoration and recovery of mine sites', *Restoration Ecology*, vol. 30, no. S2, pp. e13771.

Zedler, JB 2007, 'Success: an unclear, subjective descriptor of restoration outcomes', *Ecological Restoration*, vol. 25, no. 3, pp. 162–168.